# High Performance dynamically-loaded structures: integrating smart dampers

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## Abstract

The response of dynamically-loaded structures e.g. high-railway bridges, slender footbridges or lightweight building floors is especially dependable on structures dissipation capacity, commonly modeled as structural damping. In robotics, automation or aeronautics smart dampers are commonly used to improve comfort, safety and life span. However, their use in civil engineering structures is not common and it is only applied in singular and outstanding structures. Smart dampers are usually employed in structures as a retrofitting technique to mitigate vibration, but rarely they are incorporated from the design stage.

This paper presents a “New generation” of highly-damped slender structures which incorporate from the design stage elements that assure a minimum structural damping and bound the dynamic response. Future design of dynamically-loaded structures will go forward Damping-Based Design. Such a concept is presented hereof.

## 1 Introduction

In recent years the mechanical improvement of construction materials has enabled engineers to design lighter, slender and longer spanned structural systems with higher aesthetic quality. However, the resulting structures usually present less inherent damping which makes them more sensitive than in the past to several types of dynamic loading e.g. human-induced vibrations, wind-induced vibrations or vehicle-induced vibrations etc. (S. Zivanovic, 2005) [1]. In this context, the sizing of several structural types is commonly governed by their response under dynamic loading in terms of Vibration Serviceability Limit State (VSLS) (C.M.C. Renedo, 2019) [2].

Currently, two main design strategies can be applied to overcome the vibration issue since the design stage: the modification of the structural stiffness, and the adjustment of the system mass (J.J Connor, 2003) [3]. The first one is mainly implemented in order to avoid certain frequency ranges that could lead to an undesired dynamic response and to avoid the likelihood of resonant response. In practice, this usually means to perform structural stiffening to raise the frequency out of the critical range. Nevertheless, since structural natural frequencies are proportional to the system stiffness and inversely proportional to the mass, major structural changes are needed to sufficiently raise the frequency. Obviously, increasing stiffness is accompanied by an increase in the mass, so that significant frequency changes are difficult to achieve unless the structural layout and/or type is also changed. The second one, has been specially applied in lightweight structures e.g. stress-ribbon structures. It consists of increasing their modal mass making use of heavy concrete slabs or similar elements to improve the dynamic response (HIVOSS, 2008) [4]. Thus, throughout increasing the mass, the modal mass associated to a problematic vibration mode also increases so its resonant response is reduced proportionally. Again, an increase of the mass will be usually accompanied to a certain stiffening, leading to more massive, expensive and less efficient structures, with much higher carbon footprint.

Even though these two strategies might alleviate the vibration issue, their result are structures which are not optimized in any way: oversized, high carbon footprint, massive and expensive. Furthermore, these strategies do not act on the key parameter of the dynamic response, the structure’s energy dissipation capacity. Hence, if designers were able to increase this energy dissipation capacity, they would be able to get rid of these classical design approaches and adopt modern strategies fully used in other engineering fields. Then, more efficient dynamically-loaded structures are easily achievable, but designers need to get confident on this technologies and have at their disposal engineering approaches, supported by codes, to incorporate these technologies.

Thus, the future design of structures prone to vibrate will go forward a design approach based on acting on the structural damping. This approach has been defined as Damping-Based Design (DBD). DBD consists in a new way of designing structures in which the design principle states a minimum structural damping, to assure that the structural response under dynamic loads fulfils certain serviceability conditions e.g. VSLS. Hence, DBD is a specific case of the well-known Performance-Based Design (E. Lapointe, 2012) [5]. Its particularity responds to the fact that the required performance is achieved just by intervening on the structural damping.

In order to implement this new design approach, structural designers must make use of several and different nature damping techniques. The use of several of a set of strategies acting on the structural damping at different levels is defined here as Global Damping Strategies (GDSs). These strategies can be divided into two main classes (S. Zivanovic, 2005) [1].

- Dissipative strategies: those which increase the damping in terms of energy dissipated within the boundaries of the structure. This class includes all those damping mechanisms related to construction materials or structural joints.
- Dispersive or radiative strategies: based on mechanisms that propagate energy away from the structure. This class considers all sorts of Vibration Absorbers (VAs) as Viscous dampers, Tuned Vibration Absorbers (TVAs), Magneto Rheologic Dampers, Support devices, etc.

To sum up, DBD is a new approach that integrates efficiently GDS into the structural design process in order to take full advantage of these technologies by means of resizing the structures and making them lighter, slender and more comfortable.

The inspiration of DBD derives from the field of footbridge design. In recent decades the VSLS has become an obstacle to the increasing tendency to design slender and even more stunning footbridges. Nevertheless, DBD has allowed overcoming the vibration issue, providing a new strategy for further optimization of lightweight footbridges. The aim of this paper is to extend this design philosophy towards other structures subjected to dynamic loads, providing some examples in which DBD could be extremely useful. First, a conceptual explanation of the DBD approach will be provided, second, a detailed description of the different GDS will be performed, thirdly, some application examples will be described and finally some conclusions are provided.

## 2 Damping-Based Design (DBD)

### 2.1 Current Design approach and DBD

In the following section, DBD will be conceptually illustrated. First, it is important to notice that DBD will mainly affect the design process in those cases in which the dynamic response of the structure is responsible for its sizing. Primarily, there are two limit states that could limit the dynamic performance of the structure: The Fatigue Limit State (FLS) and the VSLS. In this article, the scope will be limited to the second one since it can represent better the DBD philosophy.

Figure 1 represents conceptually the main differences between the current way of facing the VSLS and the new approach based on the DBD. This is based on the two-step scheme. This outline allows the designer to organise more clearly the design process, performing first the conventional calculations for finally dealing with the dynamic problem separately. Moreover, the integration of GDS into the second phase enables to limit efficiently the dynamic response and so, to overcome the VSLS which will no longer be the sizing limit state. So, GDS are the main tool that enables to fulfil VSLS in the most efficient way.

When implementing damping strategies based on dissipative mechanisms, the proposed flowchart can be slightly modified. As these strategies are closely related to the inherent structural components, some resizing could be required in order to achieve proper dynamic performance. Although, it is expected that future characterization of these tools, will integrate them better into the design process.

To conclude, it is capital to underline that uncertainty is an important point that must be considered when performing dynamic analysis of structures, especially, at the design stage (S. Zivanovic, 2010) [6]. This is one of the key points in contrast to the static analysis, since structural dynamics is not always properly considered by many structural codes. Additionally, it has been proven that many dynamic parameters, as natural frequencies, structural damping or modal mass, have large variability ranges since they are extremely sensitive to several typological, constructive and operational conditions (J. F. Jiménez-Alonso, 2017) [7], (H. Bachman, 1995) [8].

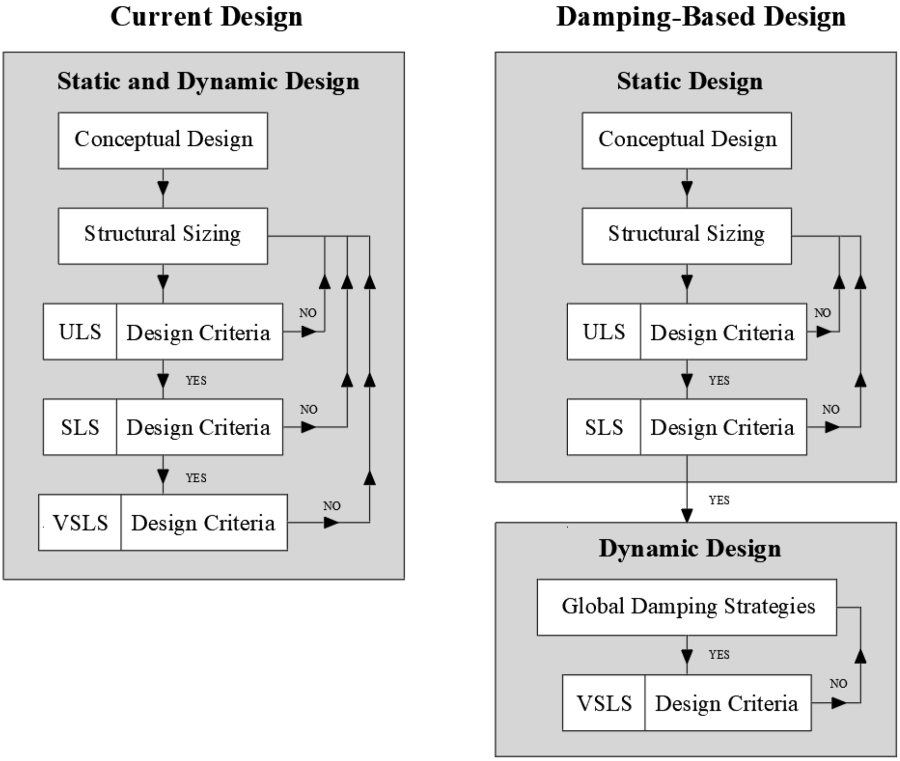

Fig. 1 Current design strategies based on structural stiffening (Left) in order to fulfil VSLS against DBD approach (Right) which integrates efficiently GDS since the design stage in order to fulfil VSLS.

## 2.2 Global Damping Strategies (GDS)

This section provides a brief explanation of the different strategies that can be considered on the design stage.

### 2.2.1 Dissipative Strategies

This category embraces all those strategies based on energy dissipation within the own structural matrix. Energy dissipation is mainly achieved due to mainly three physical mechanisms: material viscous behaviour, friction and hysteresis. Each one of them contributes to the overall structural damping. Hence, three main dissipative strategies can be adopted in order to increase the final structural damping. (A. Chopra, 1995) [9]

- Material election: some materials as wood or concrete can provide higher intrinsic damping values than others as steel or aluminium. This is mainly because of the higher amount of non-linearities involved in their structural functioning, which are mainly related to frictional behaviours. (M. Pantak, 2018) [10]
- Structural joints election: certain kind of structural joints as bolts or even articulated joints tend dissipate much more energy in terms of friction than for example welded joints.

- Highly damped viscoelastic materials: in recent years it has been studied their integration in certain constructive elements as slender composite floors. This material has been implemented as a constrained thin layer between a concrete slab and a steel beam. Vibration subjects this viscoelastic layer to cyclical shear deformation episodes in which a hysteretic shear mechanism is developed by the material, dissipating energy and so, increasing the damping.
- Viscous dampers within the structure: Viscous dampers can be implemented between structural points for dissipating energy locally within the structural boundaries. Probably the best example of this strategy is their application in cables of cable-stayed bridges to mitigate wind-induced vibrations.

### 2.2.2 Radiative or Dispersive Strategies

This terminology involves all those strategies which are based on energy propagation away from the structure. Commonly, this energy radiation out of the structural system is achieved by making use of VAs. Within all the proposed strategies, the following ones are the most commonly used.

- TVAs: They commonly consist of a mass-spring-damper system, attached to the main structure and tuned to a certain structural frequency (SAMCO, 2006) [11]. Hence, when that natural frequency is excited, the damper will resonate in opposite phase with the structural motion, absorbing an important amount of energy and so, increasing the structural damping. Passive TVAs, also known as Tuned Mass Dampers (TMDs) are effective under resonance conditions, so they can be considered as a narrow-band damping technology (H. Bachmann, 1995) [12]. However, currently, more evolved semiactive and active versions enable to mitigate broad-band vibration episodes enhancing the structural performance a lot (J. M. Soria, 2017) [13] (P. Reynolds, 2003) [14] Despite the fact of being one of the most promising technologies for increasing the structural damping efficiently, their integration into the structural design stage has been poorly studied.
- Magneto-Rheological Dampers (MR Dampers) and hysteretic support devices: MR dampers can be beneficial when located at supports as they can be used as fuse elements. This can be done due to two main properties of MR dampers: dry friction and hysteretic behaviour. when the MR damper withstands a ground reaction higher than its dry friction it begins to experience a hysteretic behaviour, and so, the system damping increases drastically. Furthermore, as support stiffness conditions changes, the frequency content of the structure will also change which results to be positive in the case of rhythmic dynamic loads. Another interesting application of MR Dampers would rely on applying them as active isolation systems also located at structural supports or bearings.

## 3 Application examples of DBD

In this section some application examples of the DBD approach will be illustrated in different structural types and with different GDSs.

### 3.1 Slender Composite-box-girder footbridge with integrated TMD

As stated before, aesthetic sense and conceptual design considerations together with the creation of more efficient materials have allowed engineers to design longer spanned, slender and lighter footbridges more prone to vibrate. In this context, the result is that it is difficult to design high quality footbridges with high vibration performance, since their first natural frequencies usually tends to be within the critical frequency ranges, defined by the first harmonic of the pedestrian walking load (especially critical from 1.6 to 2.2 Hz) and the first harmonic of the pedestrian jogging load ( from 2.2 to 3.2 Hz). This phenomenon becomes critical above 50 m of span length, where a slight variation of stiffness has no effect on the dynamic response of the structure. In those cases, the best way to control the dynamic response is the integration of a GDS at the design stage. In other words, the design can be carried out following the DBD approach.

In this case, a good technology that could be applicable as damping strategy, is the implementation of a passive TVA. This means to choose a lighter and flexible solution complemented with a damping device, instead of a much stiffer or massive solution as illustrated in Figure 2. Obviously, this damping strategy is just valid if the problematic structural natural frequencies are well separated and spatially decoupled.

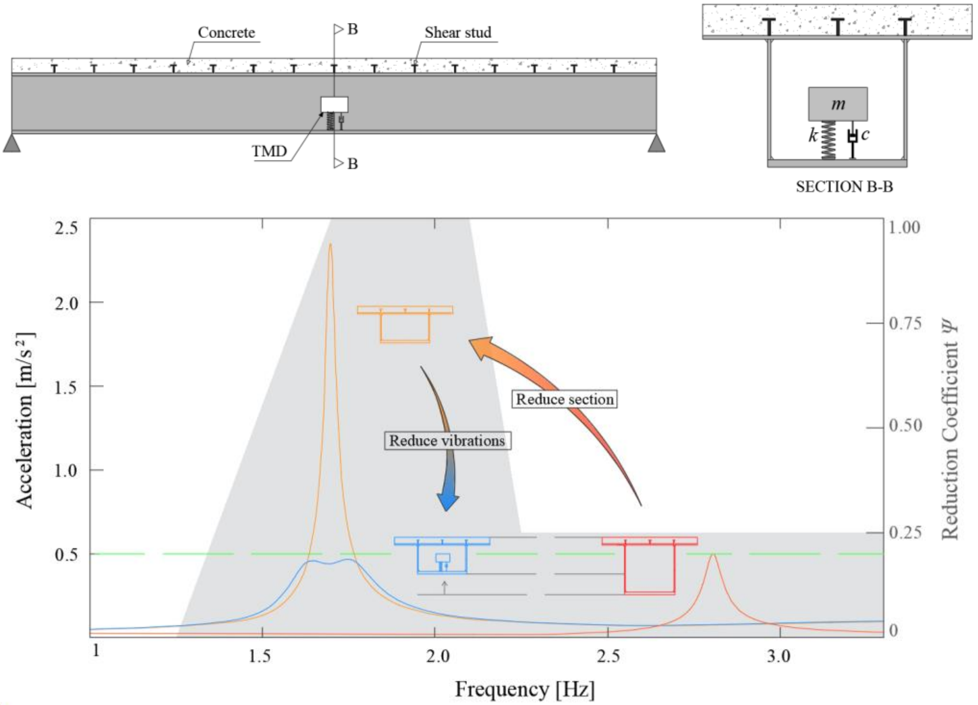

Fig. 2 Design of a footbridge with an integrated TVA. Configuration of the design scheme (above). DBD approach description (below): motion-based design based on structural stiffening (red), DBD (blue), first harmonic of walking and jogging pedestrian load (grey area) (HIVOSS, 2008) [4].

In order to apply the DBD approach, some serviceability prerequisites must be stated in relation to different service loading cases, following the performance-based design philosophy. These serviceability conditions are commonly related to comfort in terms of acceleration, usually limited to 0.5 $\mathrm{m}/s^2$ for the most usual pedestrian traffic class.

Recently, the author has designed a composite-box-girder footbridge, incorporating from the design process a TVA at mid span to meet the VSLS due to mainly the first harmonic of the walking and jogging pedestrian loads. The advantages of such a design are described and clearly shown in Figure 2. (C.M.C. Renedo, 2019) [2]

## 3.2 Slender and long composite floors with integrated viscoelastic materials or viscoelastic TMDs

Trending in modern office layouts together with new high-strength materials are changing the dynamic properties of floor systems. The removal of solid partitions walls and heavy office furnishing results in a drastic reduction of both, load and damping. Consequently, modern office floors are much slender and lightweight, which makes them more prone to vibrate.

Due to span and support stiffness constraints, critical frequency ranges for floor systems usually match with the third harmonic of the pedestrian walking force (from 5 to 8 Hz). Furthermore, modern office floor systems usually have values of damping around 2 % or 3 % (T. H. Nguyen, 2011) [15]. However, the major restrictions which make necessary to perform dynamic analysis, are the strict comfort levels required for these spaces (0.02-0.04 $\mathrm{m}/s^2$), as people are even more sensitive to vibrations in calm environments like offices (A. L. Smith, 2007) [16].

A variety of damping strategies to mitigate floor vibrations have been used with different levels of success. Here there have been presented two of the most successful proposals by (M. Wilford, 2005) [17] and (T. H. Nguyen, 2011) [15].

On the one hand, Wilford presents a solution based on a steel concrete composite floor with an integrated viscoelastic layer, that dissipates vibrations through shear deformation mechanisms. On the other hand, Nguyen solves the vibration issue by integrating a set of innovative flatten TMDs based on the idea of a cantilever sandwich beam with viscoelastic material in the middle.

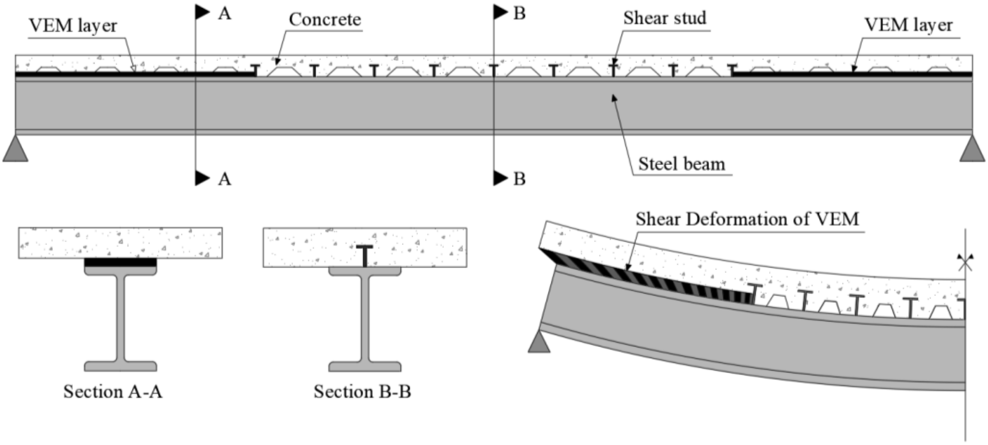

Fig. 3 Wilford,2006 system with Viscoelastic material (VEM) layer between concrete and steel. Front view (above), sections (below, left) and damping mechanism (below right).

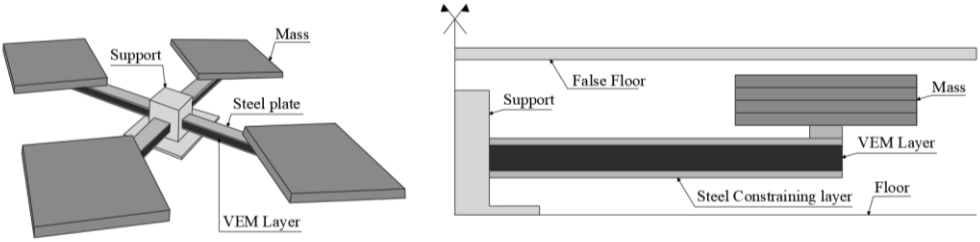

Fig. 4 Flatten sandwich viscoelastic TMDs proposed by Nguyen, 2011. Perspective view (left) section view (right).

### 3.3 Stadium grandstand with MR damper located at supports

Stadiums are one of the most expressive structural types, thus, architectural criterion is capital in their design so slenderness and amazement result to be common characteristics of these places. As a result, some modern stadium grandstands have presented vibration problems, related to fans jumping when celebrating victories or when singing hymns of teams (K. A. Salyards, 2010) [18].

A creative solution that could solve these issues is the installation of MR Dampers in at least one support of the grandstand. This would allow to change the frequency content of the structure when it is subjected to critical dynamic loadings.

When certain bearing reaction value is reached, the MR Damper's dry friction is overcome and so, a radiative hysteretic movement starts. This motion changes the stiffness of the support and hence, the natural frequencies of the harrow decrease, which tend to decrease the resonant behaviour acting as vibration isolation. Moreover, the damping of the structure increases as a result of this hysteretic energy radiation. Consequently, the dynamic performance of the structure result to be quite better.

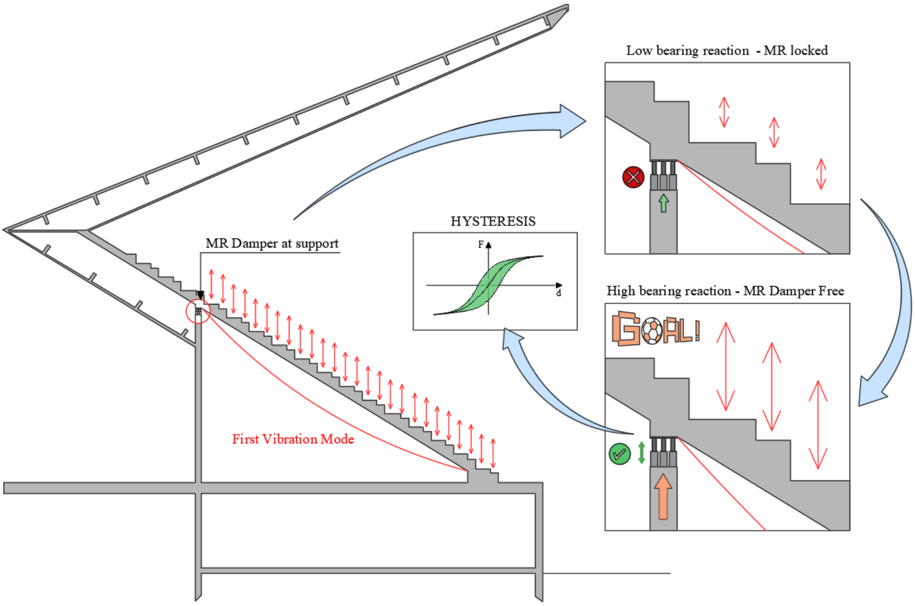

Fig. 5 Slender stadium grandstand with MR Dampers at upper bearing wall.

## 4 Conclusions

Modern aesthetical trends and new high-strength construction materials enable to design slender, more spanned and more lightweight structural types with high architectural value and reduced environmental impact. Nevertheless, these new structural designs, commonly present lower structural damping, and result to be more sensitive to human and wind-induced vibrations due to their lower natural frequencies. In this context, the sizing of an increasingly number of modern structures is governed by their VSLS. Current solutions to this problem since the design stage are based on modifying the mass or the stiffness of the structure. However, these strategies cannot be considered as optimum ones, since they do not try adjusting the most influential parameter on the dynamic response, the damping. In this paper, the authors propose a new design approach named here as Damping Based-Design (DBD) that enables to design efficiently lively structures. DBD is an emerging philosophy based on integrating Global Damping Strategies (GDSs) into the structural design process, in order to provide a minimum required damping to the structure. As a result, innovative and state-of-the-art structural types can be designed without oversizing them to obtain a successful dynamic performance.

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